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ANALYSIS OF THE POTENTIAL IMPACT OF ADDITIVE MANUFACTURING ON ARMY LOGISTICS

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December 2013

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ANALYSIS OF THE POTENTIAL IMPACT OF ADDITIVE MANUFACTURING ON ARMY LOGISTICS

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This study examines additive manufacturing and describes the potential impact it could have on Army logistics, specifically contingency resupply operations. We research the three primary methods of additive manufacturing: sterolithography, selective laser sintering, and fused deposition modeling. Our research identifies how each process works, the varieties of materials used, and the build times utilized in each process. Our methodology examines industry and military applications of additive manufacturing and identifies advantages and disadvantages of its use. Our analysis examines aerial resupply operations during Operation Iraqi Freedom and the Department of Defense standard times for aerial resupply associated with each step in the process. A comparative analysis identifies how the availability of additive manufacturing at the point of embarkation could impact order-to-receipt time of repair parts. This study concludes with the identification of the pros and cons of additive manufacturing, its potential impact on future operations, and recommendations for further research.

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LIST OF ACRONYMS AND ABBREVIATIONS

AM	additive manufacturing
ASL	authorized stockage list
APOD	aerial port of debarkation
APOE	aerial port of embarkation
CAD	computer-aided design
CCP	container consolidation point
CNC	computer numerical control
CONUS	Continental United States
CSC	Computer Sciences Corporation
DoD	Department of Defense
DMLS	direct metal laser sintering
ECD	environmental control ducting
EFOGM	Enhanced Fiber Optic Guided Missile
EOIR	electro-optical infrared
EOS	Electro Optical Systems
FDM	fused deposition modeling
ICP	inventory control point
IED	improvised explosive device
IPT	Integrated Product Team
MILALOC	military air line of communication
OIF	Operation Iraqi Freedom
POD	point of debarkation
POE	point of embarkation
REF	rapid equipping force
SLA	stereolithography
SLS	selective laser sintering
SSA	supply support activities
TDD	time-definite delivery

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I. INTRODUCTION

A. BACKGROUND

Additive manufacturing (AM) is the process of creating a three-dimensional object consisting of two-dimensional layers. Additive manufacturing technology has been steadily evolving for nearly three decades. As the technology improves and prices decrease, more industries are incorporating AM into their operations (Computer Sciences Corporation [CSC], 2012; Overton, 2009). In a deployed environment, the Army relies heavily on supply chain management to conduct operations. However, with rapid acquisition of equipment in recent years, users often identify problems associated with equipment post-deployment. Units typically deploy with a limited number of spare parts, otherwise known as an authorized stockage list (ASL). In the event of ASL depletion, or failure of parts that are not a part of the ASL, deployed units have to order parts and have them shipped from the United States. Additive manufacturing could provide the Army with the ability to produce or modify parts in the deployed environment. The ability to produce parts in theater could greatly reduce the time to get parts to the field, resulting in reduced downtime and increased operational availability of equipment.

B. PURPOSE OF RESEARCH

The overall purpose of this research is to understand how AM works and the potential positive and negative aspects of incorporating AM into operations. We examined the industrial and military applications to identify the benefits and limitations experienced as a result of AM's use. We then determined the process of creating a part and the time required to build a part.

Next, we researched aerial resupply operations during Operation Iraqi Freedom (OIF) and the Department of Defense (DoD) time-definite delivery (TDD) standards to identify the steps and associated times of the process. We set up the steps associated with aerial resupply operations and the amount of time each step takes in the form of a process timeline. Then, we constructed a theoretical timeline inserting AM capabilities at the point of embarkation (POE) in order to examine the difference in order-to-receipt time.

C. RESEARCH QUESTIONS

In order to examine the potential benefits of incorporating AM into Army logistics in a deployed environment, we attempt to answer the following questions:

1. Primary Question

- How can incorporating AM into Army operations in a deployed environment impact resupply operations?

2. Secondary Questions

- What benefits have been realized as a result of incorporating AM in industry?
- What are the limitations of AM?

D. BENEFITS OF RESEARCH

Although invented in the 1980s, AM has rapidly evolved over the past decade (CSC, 2012; Johnston, 2011). Many different methods, along with an increasing variety of materials, are used for creating 3-D objects. Just as industries are starting to utilize AM, the Department of Defense (DoD) is also capitalizing on the benefits of this emerging technology. Although the technology is not fully matured to the point of becoming a replacement for traditional manufacturing methods, some researchers have speculated that industry may be on the verge of the next revolution (De Jong & De Bruijn, 2013; Johnston, 2011). Our research examines the industrial applications of AM and documents the advantages and disadvantages of its use. We use the knowledge gained from industrial applications to formulate an example of how the Army may benefit from this technology in the future.

E. LIMITATIONS OF RESEARCH

Additive manufacturing is an evolving technology utilizing various methods and materials for generating 3-D objects. In order to concentrate our research efforts, we focused mainly on the primary AM methods and materials. The time required to build an object varies according to method, size, material used, and post-build processing procedures. Because of these variances, we used average times and assumptions for our analysis.

Unfortunately, we do not have access to the various types of AM machines and software in order to conduct an experiment. Therefore, we utilized scholarly journals, articles, and other media to conduct our research. Our research did not allow a comprehensive review of all of the advantages and disadvantages of AM. Because of the overwhelming number of industry applications, our research focused on a limited number of industries and applications. We used only industry examples with adequate information. While there are many current military applications of AM, for the sake of brevity, we only highlighted a few for illustrative purposes.

Finally, although there have been many challenges faced by the Army in logistics operations during the wars in Iraq and Afghanistan, our research is limited to reported information. There are many factors that determine average customer wait time for parts resupply, including, but not limited to, classification, priority, method of shipment, and availability. Due to these variances, we limited our data for analysis to the TDD standards located in Appendix 8 of Department of Defense (DoD) Regulation 4140.1-R (Office of the Deputy Under Secretary of Defense for Logistics and Materiel Readiness [DUSD (L&MR)], 2003). The distance between the location of the AM capability and final destination can greatly alter the amount of time it takes for a customer to receive a part. For analytical purposes, we utilized the point of debarkation (POD) Kuwait.

F. METHODOLOGY

We conducted this research by collecting data from printed reports, scholarly articles, corporate correspondence, regulations, and government research reports. Industry and military examples of AM use provided insight to both the benefits and limitations of the technology. Our collection of build time data enabled us to establish an average part production time for our analysis. We then researched resupply operations and collected data in order to develop a process timeline for analysis. The part production time averages were then used to illustrate the potential impact of having AM capabilities in theater.

G. ORGANIZATION OF REPORT

This report consists of six chapters. Chapter I includes background information, purpose of the research, benefits and limitations, and methodology of the research. Chapter II consists of the literature review. In the literature review, we examine the different AM processes, industry applications, military applications, and the future of AM. In Chapter III, we examine the Army logistics resupply process during OIF, describe challenges associated with resupply operations, and describe the standard TDD standards. In Chapter IV, we describe the methodology of data collection, detail the modeling process, and describe the analysis methods used. In Chapter V, we cover the analysis and describe the results. Finally, in Chapter VI, we detail the findings of our research, make recommendations based on our results, and conclude with recommendations for further research.

H. SUMMARY

The purpose of this chapter was to introduce AM and provide background information on its potential use in military operations. We described the research questions, benefits, limitations, and methodology behind our research. In Chapter II, we examine the AM process, benefits, limitations, industry and military applications, and the future of AM.

II. LITERATURE REVIEW

A. INTRODUCTION

In order to examine how AM can impact Army logistics operations, we examined published research and documentation on the subject. Our purpose was to examine how AM can specifically impact the parts resupply process during combat operations. First, we introduced the basic fundamentals of the AM process. Next, we examined the primary methods of building 3-D objects layer-by-layer. The examination of the primary methods provided the baseline characteristics for building a process timeline for comparison. We then examined current industry usage of AM to determine the impact on operations. Next, we researched current military applications to demonstrate the impact AM is already having on military operations. Finally, we introduced some potential future applications of AM that are under development.

B. ADDITIVE MANUFACTURING

Additive manufacturing is “the production of three-dimensional objects by layer-by-layer addition of material according to a geometrical computer model” (Mcnulty, Arnas & Campbell, 2012, p. 1). Van Cleave (2010) stated:

> Additive manufacturing produces parts by building up layers of a part’s cross sections rather than removing material, as with conventional machining operation such as milling, boring, and drilling. A single additive manufacturing machine can produce an extremely wide range of parts; it just needs the computer-aided design (CAD) data to make any given part. Depending on the specific process and materials, the parts can be simple plastic objects, or intricate metal parts for cars and aircraft. (p. 1)

One of the advantages of the AM process over subtractive processes, such as computer numerical control (CNC), is a reduction in waste. According to Freedman (2012), “Unlike machining processes, which can leave up to 90 percent of the material on the floor, 3-D printing leaves virtually no waste” (p. 52). Another advantage is the ability to make complex shapes at much lower costs, with shorter lead-times (Shulman, Spradling & Hoag, 2012). The most common, and perhaps most beneficial, aspect of

AM is the ability to rapidly create physical prototypes to aid in the development of producing final products (Gibbs and Winkelmann, 2006; Overton, 2009).

C. ADDITIVE MANUFACTURING METHODS

1. Stereolithography

The first primary AM method that we researched is stereolithography (SLA). Freedman (2012) stated, “Additive manufacturing, as 3-D printing is also known, emerged in the mid-1980s after Charles Hull invented what he called stereolithography, in which the top layer of a pool of resin is hardened by an ultraviolet laser” (p. 50). Minor and Lasater (1997) described the build process of stereolithography as follows:

> The build process uses these cross-sections of the part as patterns. A laser beam traces out and fills in each of these cross sections on the surface of a vat of liquid photocurable resin. Wherever the laser traces, the liquid resin is cured to a solid, to a depth of approximately 0.006 to 0.009 inches. Once the entire cross-section is cured, the part is dipped into the liquid to recoat the part with liquid resin. The laser then traces out the next cross-section on top of the previous one. This process is repeated until all of the cross-sections of the part have been cured. At which time, the completed prototyped part emerges from the liquid. (p. 3)

According to Hormozi (2013), stereolithographic parts have numerous applications. Hormozi stated, “They can be used to mimic production parts for functional testing and evaluation as well as for production of parts for concept models, or the concept models themselves” (p. 46). Gibbs and Winkelmann (2006) stated, “The build rate for SLA parts is approximately 1 cubic inch/hour, which for most parts makes it the fastest process available” (p. 24). They continued, “It is also capable of building the largest parts available, with a maximum envelope of 25 × 30 × 22 inches” (p. 24). According to Brain (2000), a build processing time ranges from six to 12 hours. Figure 1 is a graphic illustration of how SLA works.

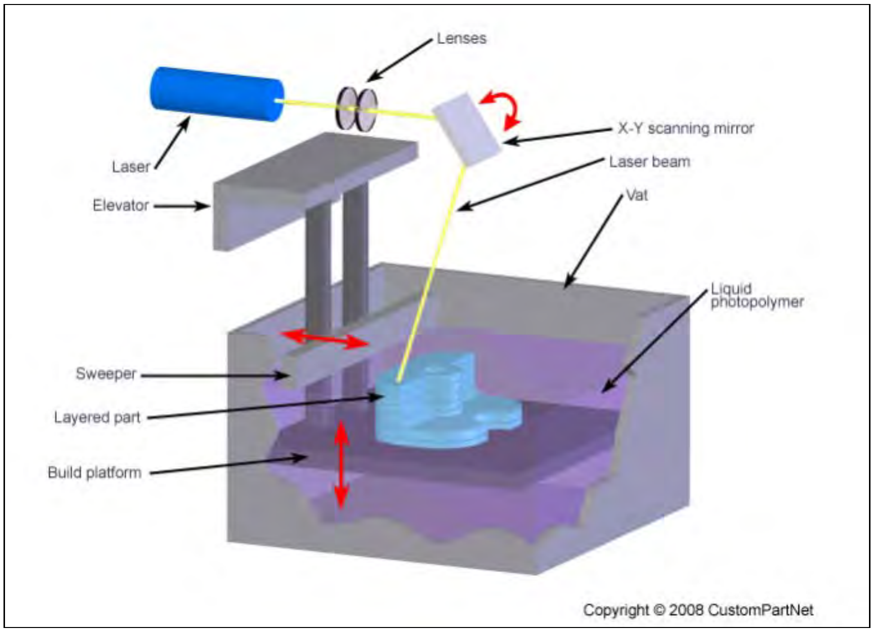

Figure 1. Diagram of SLA Process (from Stereolithography, 2008)

As demonstrated in Figure 1, a laser is sent through a series of lenses into a scanning mirror that directs the beam along an X and Y axis in order to solidify the photopolymer. An elevator lowers the build platform after each layer of the build is completed. Once the platform lowers, a sweeper moves across the liquid photopolymer to ensure the proper thickness of liquid is present to create the next layer. Once all layers have been created, the elevator lifts the build platform, revealing the finished product.

2. Fused Deposition Modeling

The second primary method of AM that we researched was fused deposition modeling (FDM). According to Vartanian (2013), "In FDM, a plastic filament is unwound from a coil and supplies material to an extrusion nozzle, which can turn the flow on and off. . . . The nozzle is heated to melt the material and is moved in both the horizontal and vertical directions by a motion control mechanism, driven by a tool path created directly from a CAD model" (p. 52). Gibbs and Winkelmann (2006) explained, "FDM parts can achieve a layer thickness of 0.004 to 0.020 inches, and the build rate for this process is approximately 1 cubic inch/hour with a maximum envelope of 24 × 20 × 24" (p. 25). Figure 2 illustrates the FDM process.

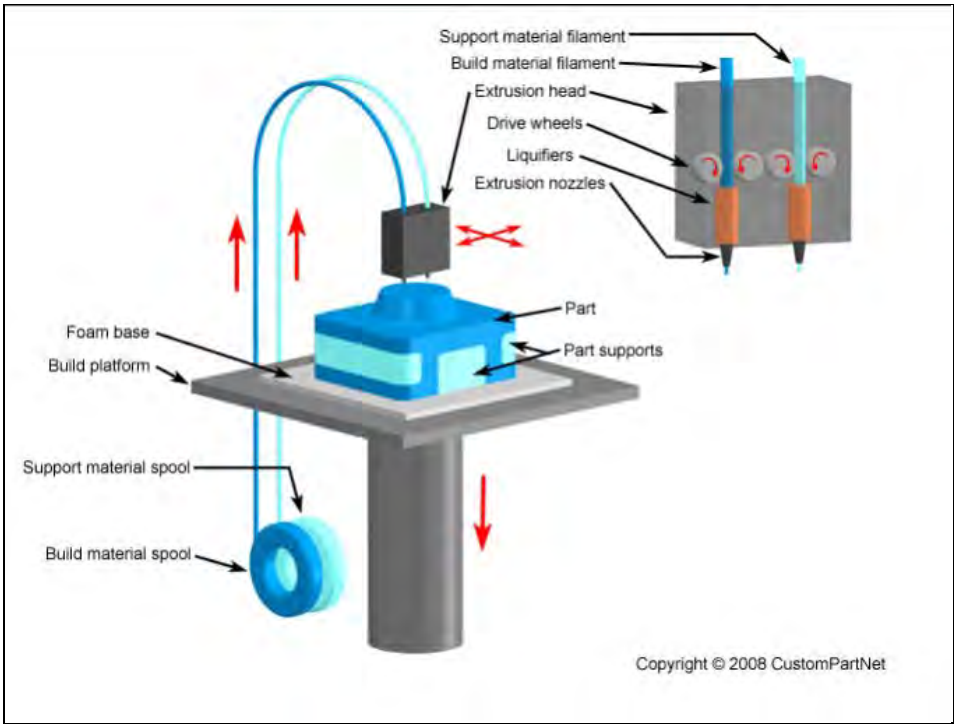

Figure 2. FDM Diagram (from Fused Deposition Modeling, 2008)

As demonstrated in Figure 2, build material and support material on spools are fed through an extrusion head that force out the material onto a foam base on a build platform. The FDM extrusion head moves along the X and Y axis. As build and support material is fed through the extrusion head by drive wheels, liquefiers heat the material, and the material is deposited. After each layer is deposited, the build platform lowers in preparation for the next layer. Once all layers have been deposited, the support material is discarded.

3. Selective Laser Sintering

The third and final primary method of AM we researched was selective layer sintering (SLS). According to Freedman (2012):

> In sintering, a thin layer of powdered metal or thermoplastic is exposed to a laser or electron beam that fuses the material into a solid in designated areas; then a new coating of powder is laid on top and the process repeated. (p. 52)

Gibbs and Winkelmann (2006) stated, “The build rates for SLS is [*sic*] between 0.25 to 1 cubic inch/hour and the largest parts that can be made through the process are 22 x 22 x 30 in” (p. 25). Metal parts can also be created from the SLS process through direct metal laser sintering (DMLS; Wong & Hernandez, 2012). Figure 3 is an illustration of the SLS process.

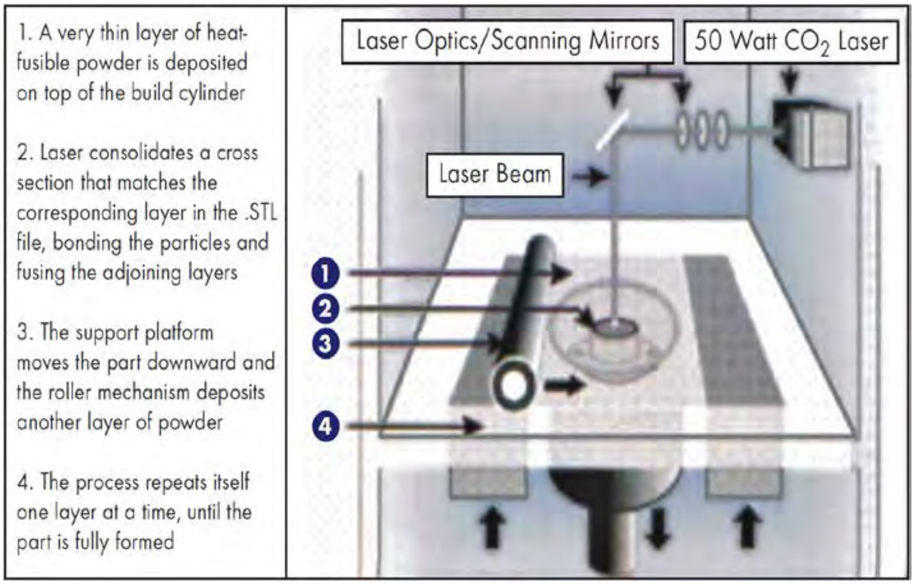

Figure 3. Selective Laser Sintering Process (from Fink, 2009, p. 8)

As shown in Figure 3, a very thin layer of heat-fusible powder is deposited on top of the build cylinder via a roller. Once an even layer of powder has been deposited, the laser bonds the powder together. After a layer has been completed, the build platform lowers, and another layer of powder is deposited. Once all layers have been deposited, the build platform raises, excess powder is removed, and the finished product is revealed.

According to Wong and Hernandez (2012),

> The main advantages of this technology are the wide range of materials that can be used. Unused powder can be recycled. The disadvantages are that the accuracy is limited by the size of particles of the material, oxidation needs to be avoided by executing the process in an inert gas atmosphere and for the process to occur at constant temperature near the melting point. (p. 5)

D. INDUSTRY EXAMPLES

1. Aerospace

The Computer Sciences Corporation (CSC) produced a technology program highlighting the state of AM during the Leading Edge Forum titled *3D Printing and the Future of Additive Manufacturing*. In the program, CSC highlighted the successful use of 3-D printing by several industries, including the aerospace industry. An example of an aerospace company utilizing AM with great success is Boeing. CSC (2012) described Boeing's experience using AM as follows:

> Boeing, a pioneer in 3D printing, has printed 22,000 components that are used in a variety of aircraft. For example, Boeing has used 3D printing to produce environmental control ducting (ECD) for its new 787 aircraft. With traditional techniques, the ECD is created from up to 20 parts due to its complex internal structure. However, with 3D printing, Boeing produces the ECD as one piece. The new component reduces inventory, does not require assembly and improves inspection and maintenance times. As the 3D–printed parts weigh less, the aircraft's operating weight decreases, resulting in fuel savings. (p. 10)

Figure 4 is an example of an aircraft part created utilizing AM.

Figure 4. 3-D Printed Metal Airbus Wing Bracket (from CSC, 2012, p. 10)

This aerospace industry example illustrates how AM can reduce the number of parts required for assembly, reduce weight, and improve performance.

2. Dentistry

Johnston (2011) describes the tremendous impact AM has had on the dental industry in his article, "3-D Printing: The Future Comes Around Again:"

> 3-D printing is making rapid headway in the dental market. Medical imaging technologies are making it possible to create a digital prototype of a mouth, which can be used to design and 3-D print dental prosthetics, rather than molding and casting them. This same combination of technologies is either lowering the skill requirements for implantation or enabling dental surgeons to make better and safer use of the skills they possess. This change is being brought about by the 3-D printing of drill guides, which enables the doctor to put the hole in a patient's jawbone exactly where it is supposed to be. (p. 7)

Overton (2009) quoted Martin Bullemer, key account manager, medical, at Electro Optical Systems (EOS), who stated, "Direct metal laser sintering is used by dental labs to create copings and bridges; the EOSINT M 270 builds customized dental prostheses in batches of 200 or more, dramatically increasing lab output while meeting stringent quality standards" (Overton, 2009, p. 45). The EOSINT M 270 is a model of DMLS machine. Figure 5 is an example of a DMLS product.

Figure 5. Dental Implants Made From CAD File Using DMLS (from Overton, 2009, p. 45)

This implant is just one example of many applications of AM in the field of dentistry. Additive manufacturing has also been used to create customized alignment devices and has even been used to create a titanium jaw (CSC, 2012). These examples illustrate that AM increases output, improves safety, and eliminates steps required to produce implants.

3. Health Care

There are many uses of AM in the health care industry. Two examples of AM applications are implants and prosthetics. Regarding the use of AM for medical implants, CSC (2012) reported,

> There are a growing number of applications for 3D printing in surgery. For example, the Walter Reed Army Medical Center has created and successfully implanted over 60 titanium cranial plates. In June 2011 the first 3D–printed jaw, also made of titanium, was successfully implanted in an 83-year-old woman by Dr. Jules Poukens of Hasselt University. These implants perfectly match a patient's body and provide better fixation, which can reduce surgery time and infection. (pp. 12–13)

Concerning the use of AM for prosthetics, CSC (2012) stated,

> Perfectly matching a person's body is key for prosthetic devices too. 3D printing is ideal for these highly customized, small production runs (quantities of one) that demand strong but light-weight materials. 3D printing would enable those with limb loss to get exactly what they want for look, feel, size and weight, all for a fraction of the cost of a traditionally-made prosthetic. (p. 13)

Medical implants and prosthetics are only two examples of the many uses of AM in the health care industry. These examples illustrate how AM is ideal for low volume manufacturing while producing highly customizable objects with low cost. While low volume production would be considered a limitation in some industries, the health care industry is ideal for this type of application.

4. Manufacturing

Additive manufacturing has been successfully incorporated into the manufacturing industry as well. According to CSC (2012),

> Thogus Products, a custom plastic injection molder, found that for a particular specialty part, 3D printing (the Fused Deposition Modeling or FDM method) reduced the cost of manufacturing from $10,000 to $600, the build time from 4 weeks to 24 hours, and the weight of the object by 70–90 percent. (p. 6)

Figure 6 shows the benefits realized by Thogus across three parts. Cost saving realized by Thogus ranged from 82 percent to 94 percent. Lead-time reduction across these parts ranged from 75 percent to 99 percent.

PART/ TOOL	FDM	ALTERNATIVE METHOD
End of arm robot	$600 24 hours	$10,000 4 weeks
Automated turntable	$8,800 2 weeks	$50,000 8 weeks
Steel plates	$20 2 hours	$200 2 weeks

Figure 6. Benefits of FDM Used by Thogus Products (from CSC, 2012, p. 6)

While Thogus illustrates just one example of the successful incorporation of AM, it illustrates that both cost and production time can be reduced as a result. The automotive industry has started using AM in the development and production of prototype and replacement parts as well (CSC, 2012). The ability to produce parts layer by layer also enables weight reduction of products by eliminating material that would otherwise be present if produced through traditional methods (Overton, 2009).

E. CURRENT MILITARY APPLICATIONS

The use of AM by the Army is not a recent development. Minor and Lasater (1997) described the use of stereolithography by the Enhanced Fiber Optic Guided Missile (EFOGM) Seeker Integrated Product Team (IPT) during the 1990s as a great success. However, just as the technology has evolved, the military applications have evolved as well. From prototypes to end user items, the Army is embracing the potential offered by AM.

Recently, the Army Rapid Equipping Force (REF) deployed mobile labs to Afghanistan that bring AM capabilities to the front lines. According to Hoffman (2012), “The labs cost about $2.8 million each and include state-of-the-art equipment such as a Rapid Prototyping 3D Printer, a machine that can produce plastic parts that may not even exist in the current inventory” (para. 4).

When the introduction of new improvised explosive device (IED) jammers increased the battery weight soldiers had to carry, a soldier requested that the lab create an adapter for his Army standard-issue lithium battery and use it to recharge those for the IED jamming device instead (Ruiz, 2012). According to Ruiz (2012):

> Within six hours, the lab’s two-person staff built a prototype adapter, creating plastic couplings and brackets with the 3-D printer. A week later, after the unit tested 10 adapters in the field, the soldier returned and requested 200 more. The design was sent back to an Army lab in Georgia, which is replicating 1,800 adapters that are scheduled to arrive in theater within six months. The fix means that each soldier in a platoon can shed five pounds of batteries. (para. 11–12)

CSC (2012) highlighted the successful use of 3-D printing by Electro-Optical Infrared (EOIR) Technologies as follows:

> Components used in military equipment must be strong, durable and, above all, reliable, as failure can put lives at risk. Consider the mount for camera gun sights on the M1 Abrams tank and Bradley fighting vehicles. These high-precision components are mounted on the external body of the tanks, where they must survive incredibly harsh shock, vibration and environmental conditions. EOIR Technology, a leading defense system design and development company, was able to manufacture mounts durable enough for use on the tanks using a 3D printer. What’s more, by switching to 3D printing technology, the company reduced the manufacturing costs from over $100,000 per unit to under $40,000. (p. 9)

Van Cleave (2010) highlighted the work of James Barkley, the lead software systems engineer for the MITRE organization who is leading MakeOne, a project that is researching using AM in theater. According to Van Cleave (2010), Barkley stated:

> Parts produced using additive manufacturing could be made for temporary use or even permanent replacement. You can build parts with complex geometries without conventional tools and fixtures. That reduces total manufacturing time, reduces waste, and tends to be more energy-efficient. (p. 1)

Figure 7 illustrates how part fabrication in theater could increase warfighter uptime and reduce downtime.

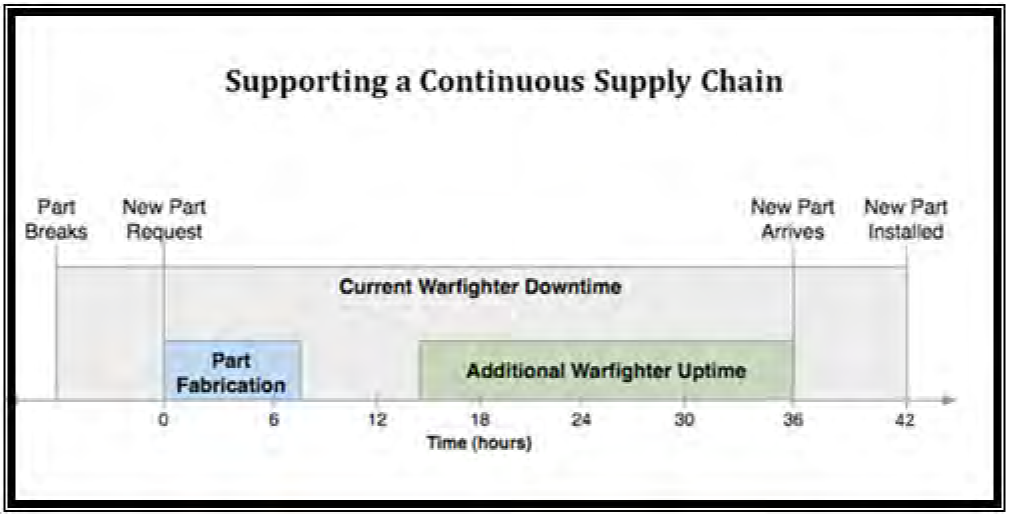

Figure 7. Comparison of Parts Replacement Using Traditional Methods Versus AM (from Van Cleave, 2010, p. 2)

According to Figure 7, once a part breaks, the warfighter downtime is approximately 42 hours. Once a new part arrives, it is installed in approximately six hours. By using AM, Barkley estimates a part can be fabricated in approximately eight hours, and warfighter uptime can be increased by approximately 22 hours.

Van Cleave (2010) also described the future challenges of making AM in-theater a reality:

> As with the process itself, 3D printing in-theater still has a few layers to add before it becomes a regular part of the supply chain process. To succeed, military equipment makers must accept the additive manufacturing process so that their computer-aided design files can be used in the field; new data standards must be developed and accepted for computer-aided design processes; and 3D printing must be simplified for

> automation. Additionally, network architectures must be developed for selecting and transmitting electronic files for a variety of parts in different sizes and materials. (pp. 3–4)

The study by the MITRE is similar to the research presented in this report in that it addresses how AM can impact resupply operations. However, as Figure 7 illustrates, the comparison is based off intra-theater resupply and assumes part availability. MITRE's study illustrates that research is ongoing toward making maintenance repair parts with AM in theater a reality.

F. THE FUTURE OF ADDITIVE MANUFACTURING

Additive manufacturing is rapidly evolving, and the potential seems unlimited. The list of usable materials and applications is constantly increasing, and quality is steadily improving (CSC, 2012). Research is currently underway regarding printing human cells to create transplantable organs. According to McNulty, Arnas, and Campbell (2012):

> Beyond their potential for revolutionizing production, 3D printers have fostered significant developments in health care. The Wake Forest Institute for Regenerative Medicine (WFIRM), based at Wake Forest University, has successfully used 3D printing technology to create human tissue. Cells were used in place of an inkjet cartridge to create a two-chamber heart. While this process is strictly experimental and not for use in patients, its potential could revolutionalize [*sic*] organ transplants. (p. 5)

Figure 8 is an illustration of 3-D printed organs.

Figure 8. 3-D Printed Kidney, Ear, and Finger (from CSC, 2012, p. 13)

While the technology is improving, printers and materials are decreasing in cost. 3-D printers are slowly making their way into the home, and more people are able to take advantage of this technology. According to De Jong and De Bruijn (2013):

> While early systems were mainly sold to large, multinational customers, 3-D printing manufacturers more recently started to focus on the lower end of the market, offering increasingly cheaper machines to make 3-D printing a viable option for small businesses, self-employed engineers and designers, schools and individual consumers. (p. 44)

Whether industry is on the verge of another revolution remains to be seen. However, it is clear that AM will continue to benefit both industry and the military for years to come.

G. SUMMARY

The goal of this chapter was to describe the primary methods of AM, provide military and industry examples of its use, and briefly introduce its future potential. As our primary source of data concerning the benefits and limitations of AM, existing literature proved insightful. In the next chapter, we discuss logistics operations in preparation for examining how AM could be beneficial in future combat operations.

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III. ARMY LOGISTICS OPERATIONS

A. INTRODUCTION

In this chapter, we focus on the Army aerial resupply process and the issues encountered during the early stages of OIF. First, we examine a study on sustainment operations during the early stages of OIF commissioned to the RAND Corporation by multiple general officers (GOs) in the sustainment community. Next, we compare the findings to the standards outlined in the *Supply Chain Materiel Management Regulation*, DoD 4140-R (Office of the DUSD [L&MR], 2003). Finally, we summarize our findings and identify relevant material for our analysis.

B. SUSTAINMENT DURING OPERATION IRAQI FREEDOM (OIF)

There were many challenges to resupply operations during the early stages of OIF. Our research focuses on issues related strictly to the replenishment of maintenance parts. The two major problems associated with parts replenishment were rapid depletion of ASLs and order consolidation prior to shipment.

An ASL consists of pre-identified spare parts that are stored at the brigade level and assigned supply support activities (SSA) (Peltz, 2005). Regarding problems with ASLs, Peltz (2005) stated:

> Many demands for spare parts were unmet in OIF even when the right parts had been authorized for stockage. This is because the supplies of these parts were quickly depleted. There were three reasons for this: the Army did not stock the ASLs to (1) wartime operating tempo, nor did it stock to cover (2) the long replenishment wait times and (3) supply disruptions experienced in OIF. (p. 28)

Rapid depletion of replacement parts residing in brigade and SSA ASLs led to an increased number of requisitions for replacement parts from the continental United States (CONUS) (Peltz, 2005). Unfortunately, problems originating in the CONUS led to further delays in part replenishment.

One set of metrics used to identify the source of problems in the distribution system was the receipt rates and process segment times of military air line of communication (MILALOC) shipments. Military air line communication shipments refer to the use of military airlift assets to provide the link between supply operations and military units. Figure 9 illustrates these metrics for two calendar years prior to OIF and monthly statistics from January 2003 to November 2004.

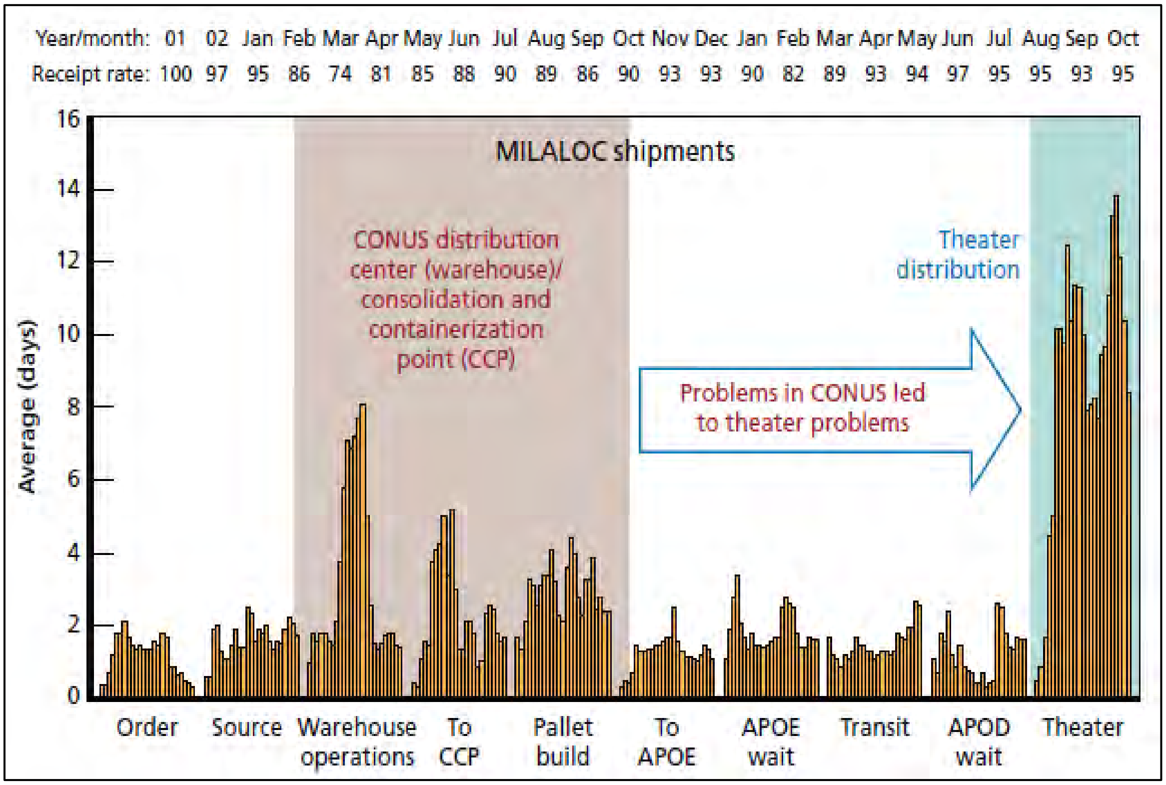

Figure 9. MILALOC Receipt Rates and Process Segment Times, CY01, CY02, and January 2003 to November 2004 (from Peltz, 2005, p. 63)

Peltz (2005) defined each column of Figure 9 as follows:

- The first segment (order) reflects a set of information processes for transmitting the order to the national supply system and reflects the time from the document date until the order is received and established in the national supply system.
- The next segment (source) is the time for the organization that manages the part to send a materiel release order to a distribution center or other supply organization, which can be either an automated or manual process.
- Warehouse operations consist of the set of processes to get an item from storage and prepare it for shipment, and they end when the item departs the warehouse or is released to the shipper.

- To CCP (container consolidation point) is the time it takes to go from the warehouse to the CCP, ending when it is receipted at the CCP. Time in this segment can come from transportation from a non-collocated distribution center or sitting in a queue waiting for CCP receipt.
- Pallet build is the time from when an individual shipment is receipted at the CCP until it is put on the pallet and the pallet is released for shipment.
- To APOE (aerial port of embarkation) reflects the time from CCP release until APOE receipt and includes transportation to the APOE and wait time on both ends.
- Once the APOE receipts the pallets, the wait time for aircraft departure is recorded in the APOE wait time segment.
- Transit reflects overseas shipment, including intermediate stops and any change of planes.
- APOD (aerial port of debarkation) wait time is how long it takes to leave the APOD once it hits the final aerial port.
- The final segment (theater) is the total time from APOD release to receipt by the requestor. (p. 63)

Figure 9 highlights that problems in the CONUS led to delays in shipments in theater. Configurations of shipments at both the APOEs and CCPs resulted in delays in theater distribution. At the CCPs, many shipments were consolidated into multipacks, which required pallets to be broken down, sorted, and repacked before distribution to combat units (Peltz, 2005). Regarding APOE operations, Peltz (2005) stated:

> They just built pallets to support efficient transportation, consolidating pallets by APOD, regardless of unit or service. … Many of these pallets were sent straight to a single division without first being broken down, even though they contained materiel for multiple divisions or nondivisional units. (p. 70)

Longer order-to-receipt times are an expected consequence of incorrectly routed shipments.

During the course of OIF, deficiencies in resupply operations were addressed and order-to-receipt times gradually dropped until they were within standards. Lieutenant General Mitchell H. Stevenson, Deputy Chief of Staff, G-3, Army Materiel Command, was one of the general officers who commissioned the RAND study. Stevenson reported that by 2010, the average customer wait time for outside the CONUS air shipments was down to just 13 days (Stevenson, 2011).

C. STANDARD OPERATING PROCEDURES

Appendix 8 of DoD 4140-R (Office of the DUSD[L&MR], 2003) lists the time-definite delivery (TDD) standards for Category 1 requisitions. A Category 1 requisition is any requisition with a priority code of 01 through 03. These priority codes regularly pertain to maintenance repair part failures that result in equipment downtime. Table 1 is the TDD standards for Category 1 requisitions by pipeline segment and area.

Table 1. Time-Definite Delivery Standards (Days) for Category 1 Requisitions (from Office of the DUSD [L&MR], 2003, p. 245)

			AREA			
PIPELINE SEGMENT	**CONUS**	**A**	**B**	**C**	**D**	**EXP**
A. Requisition Submission Time	.5	.5	.5	.5	.5	.5
B. ICP Processing Time	.5	.5	.5	.5	.5	.5
C. Storage Site (or Base) Processing, Packaging and Transportation Hold Time	1	1	1	1	1	1
D. Storage Site to CCP Transportation Time	N/A	1	1	1	1	N/A
E. CCP Processing Time	N/A	.5	.5	.5	1	N/A
F. CONUS In-Transit Time	1.5	1	1	1	1	N/A
G. POE Processing and Hold Time	N/A	3	3	3	3	N/A
H. In-transit to Theater Time	N/A	1	1	1	2.5	3
I. POD Processing Time	N/A	2	2	2	2	N/A
J. In-Transit, Within-Theater time	N/A	1	1	1	1	1
K. Receipt Take-Up Time	.5	.5	.5	.5	.5	.5
Total Order-to-Receipt Time	**4**	**12**	**12**	**12**	**14**	**6.5**

The pipeline segments in Table 1 refer to the locations of delivery. Times listed in the CONUS column refer to deliveries within the United States. Area A refers to deliveries in the vicinity of Alaska, the North Atlantic and the Caribbean (Office of the DUSD [L&MR], 2003, p. 243). Area B refers to locations in the vicinity of the United Kingdom and Northern Europe. Area C refers to locations in the vicinity of Japan, the Western Mediterranean, and Italy (Office of the DUSD[L&MR], 2003, p. 244).

For our analysis, the APOD is Kuwait. Therefore, we utilized Area D of the TDD standards. According to AP8.2.1.4 of DoD 4140-R:

> Hard lift areas—all other destinations not listed as determined by the U.S. Transportation Command; e.g., low-use Alaska (Eielson AFB, Adak, Eareckson AS, and Galena); low-use Japan (Itazuke, MCAS Iwakuni, Misawa AB); low-use Korea (Kunsan AB and Kimhae); Indian Ocean (Diego Garcia); New Zealand (Christchurch); Singapore (Paya Lebar); Greece (Souda Bay); Turkey (Incirlik AB); Southwest Asia (Saudi Arabia (Dharan and Riyadh), Kuwait, Bahrain, Oman (Fujairah)); and Israel (Tel Aviv). The time standards for port of debarkation (POD) for Area D are lower than the other areas. (p. 244)

In order to illustrate how AM could have impacted aerial resupply operations, we first compared the TDD standard times with the times experienced during the early stages of OIF illustrated in Figure 9. Unfortunately, we did not have access to the data utilized to create Figure 9, and therefore had to estimate each column represented in the graph. For each bar in Figure 9, we entered an estimated time in days according to the height of each bar into a spreadsheet. The values for each step were averaged in order to determine the average time for each step in the process. Table 1 illustrates the results of our estimates and the TDD standards.

Table 2. Estimated Order-to-Receipt Time 2001–2004 Compared to 4140-R (in Days)

	Yr./Mo	2001	2002	2003	2004 (Jan-Nov)	4140-R Standard Category 1 (Area D)
Process						
Order		0.50	0.50	1.62	1.05	0.5
Source		0.75	0.75	1.87	1.91	0.5
Warehouse Ops		1.00	1.90	4.16	2.73	1
To CCP		0.30	0.25	3.01	1.85	1
Pallet Build		1.80	1.70	3.06	3.04	1
To APOE		0.25	0.40	1.25	1.28	1
APOE Wait		1.00	1.90	1.85	2.06	3
Transit		1.75	1.15	1.26	1.81	2.5
APOD Wait		1.00	0.60	1.03	1.14	2
Theater		0.40	0.70	8.71	10.15	1.5
Total		**8.75**	**9.85**	**27.82**	**27.02**	**14.00**

Our estimates illustrated that during the early stages of OIF, average order-to-wait time was nearly double the standards set in the 4140-R. These estimates provided the average times necessary to apply them to our model in order to measure the impact AM could have in affecting order-to-wait time during combat operations. While AM is not mature enough for full-scale part replacement operations, these estimates provide us with data from an actual operation for comparison. During our analysis, only CONUS processes were eliminated. Theater estimates remained unchanged, with the assumption that the ability to produce parts in theater would not impact delays residing in theater.

D. SUMMARY

The purpose of this chapter was to identify the process of aerial resupply of parts and to establish the times associated with each step. Our research resulted in identification of each step associated with the aerial resupply process and the times according to the standards, and estimates from a recent combat operation. We identified challenges encountered during the early stages of OIF and developed estimates in order to provide the basis for application to our model and analysis. In the next chapter, we cover the methodology of our research and the development of our model for analyzing how AM could impact aerial supply operations.

IV. RESEARCH METHODOLOGY

A. INTRODUCTION

In this chapter, we explain how we collected and evaluated data in order to answer the research questions introduced in the first chapter. Next, we cover how we set up our model for analyzing our data. We then discuss our analytical process in order to determine the potential impact AM could have on the resupply process. Finally, we summarize our research up to this point.

B. METHODS USED IN DATA COLLECTION

As previously mentioned in Chapter I, we conducted this research by collecting data from printed reports, scholarly articles, corporate correspondence, regulations, and government research reports. We first utilized these resources to determine the primary methods of producing 3-D objects. Then we used them to identify advantages and disadvantages, common materials used, and build rates of each process.

Once we completed research regarding the primary methods of AM, we utilized our resources to examine some examples of industry use of manufacturing. Through our examination of industry applications, we identified examples of benefits realized as a result of incorporating AM. Next, we utilized our resources to examine several examples of past and current applications of AM by the Army. Through our study of Army applications, we identified benefits already experienced. The final step in our research on AM was identifying what our sources said about the future of this evolving technology in order to illustrate its future potential.

After concluding our research on AM, we researched resupply operations during the early years of Operation Iraqi Freedom. By examining a government study on resupply operations, we identified the timeline and processes associated with aerial resupply. Aerial resupply is most commonly used for shipping high priority parts to theater; therefore, we focused our research there. Next, we consulted DoD Regulation 4140-R (Office of the DUSD [L&MR], 2003), which identifies time delivery standards for resupply operations, in order to compare the standards to early OIF operations.

C. SETTING UP THE MODEL

In order to evaluate the potential benefits of AM on resupply operations during war, we set up a process flowchart. Figure 10 is a sample of the flowchart we created for our analysis.

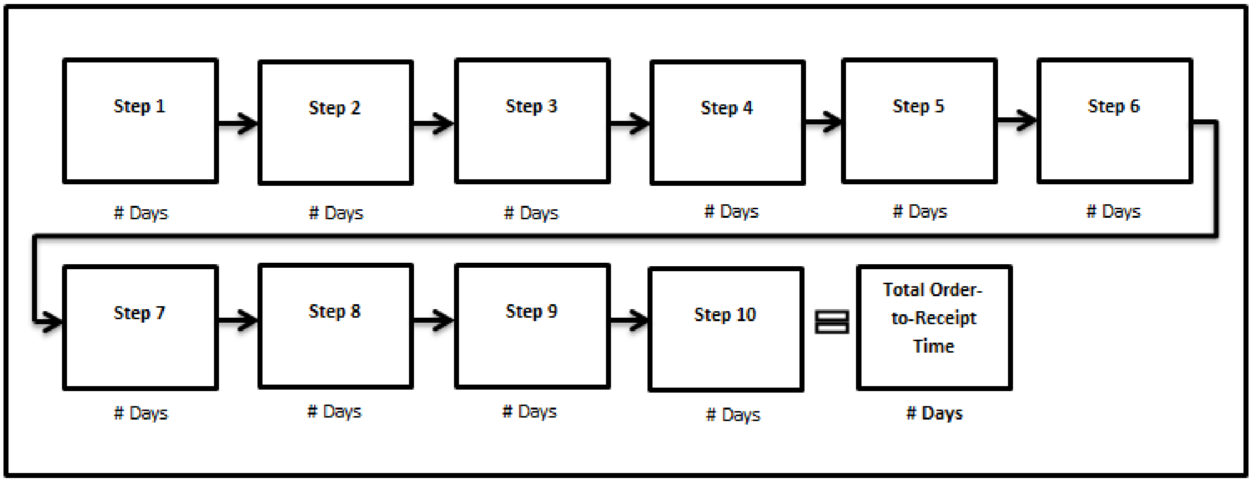

Figure 10. Sample Process Flowchart

Each block in Figure 10 represents a step in the aerial resupply process. Under each step, the amount of time associated with the corresponding step is entered. The final block represents the lead-time, referred to in supply operations as order-to-receipt time. First, we created a flowchart for standard operating procedures. Then, we created flowcharts by removing expendable steps and inserting the various AM processes. Finally, we calculated the order-to-receipt times for each process.

D. ANALYTICAL PROCESS

In order to illustrate the potential impact AM can have on Army logistics, specifically aerial resupply operations; we applied our research findings to the process flowcharts we created. Based on typical build time presented by Brain (2000), the SLA build time utilized was 12 hours. Based on a build rate of 1 cubic inch/hour as described by Gibbs and Winkelmann (2006), which is the same build rate as SLA, a 12-hour build time was utilized for FDM as well. The build rate for SLS can vary from 0.25 to 1 cubic inch/hour (Gibbs & Winkelmann, 2006). Because of this variance, we assumed a build rate of 0.5 cubic inch/hour, therefore doubling the build time of the same part to 24 hours. For DMLS, we added 12 hours to the standard build time in order to account for post-build processes required for the production of metal parts.

Dimensions and volume varies between parts, and the number of parts produced per build also varies. For the purposes of our analysis, we assumed one part is produced per build. The distance between the AM capability and the customer can positively or negatively impact order-to-customer receipt time. For the purposes of this analysis, we assume the capability resides at the point of debarkation.

E. ASSUMPTIONS

The assumptions we used to determine the potential benefits of incorporating AM in theater were as follows:

- Part produced does not exceed the dimension capabilities of the AM process used.
- CAD files for producing the part are readily available.
- Only one part is produced per run.
- Build times used include pre- and post-production processes.
- AM capability resides at the POD.
- The POD for our analysis is Kuwait.
- Parts produced meet military specification standards.
- Parts produced consist of only one material.
- Parts produced are Category 1 requisitions with priority designators 01 through 03.
- Adequate build material is available for part generation.

For our assumptions, we limited the size of the part being produced to the dimensions of the machine. While larger parts could be built in smaller pieces and later assembled, for analysis purposes and for the sake of consistency, we assumed that only individual parts that met the dimension criteria are produced. We also assumed that build material is readily available at the POD. We chose Kuwait as our POD because it is the primary distribution center for inbound shipments of parts en route to Iraq.

F. SUMMARY

In this chapter, we covered the methodology and analytical process utilized in order to determine the potential impact AM can have on resupply operations in future combat operations. In Chapter V, we conduct our analysis based on our model and discuss our findings. In Chapter VI, we conclude our research project with a summary of our findings and recommendations for further research.

V. ANALYSIS AND RESULTS

A. INTRODUCTION

In this chapter, we apply our assumptions to the process flowchart we developed in Chapter IV. First, we insert the steps described in the TDD standards into our process flowchart to establish a baseline model for comparison. Next, we substitute AM processes and remove the process steps that were eliminated as a result. Then, we incorporate the process times experienced in the early stages of OIF into our model to illustrate how AM could have impacted operations. Finally, we summarize our findings.

B. ORDER-TO-RECEIPT TIME ANALYSIS

1. TDD Standards

The first step in our analysis was to incorporate the TDD standards into our process flowchart. Figure 11 is a resupply operations process flowchart including the standard processes and times associated with each.

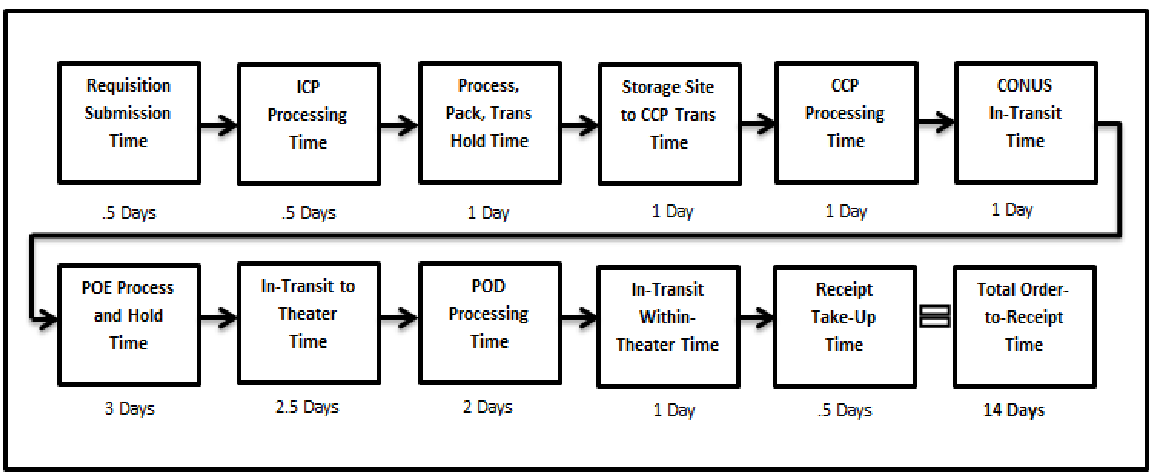

Figure 11. Resupply Process Flowchart for Category 1, Area D

Figure 11 includes the steps and process times listed in Table 1. The POD utilized for our analysis was Kuwait. As a result, we utilized the TDD standards listed in column “Area D” in accordance with DoD 4140-R, AP8.2.1.4. The TDD standard for total order-to-receipt time for resupply operations to Kuwait is 14 days.

2. Incorporating SLA

Next, we incorporated SLA into our flowchart and eliminated the steps associated with processing and delivering parts in the CONUS. The times associated with all other steps in the process were unchanged. Figure 12 represents our process flowchart illustrating the incorporation of SLA into the aerial resupply operation.

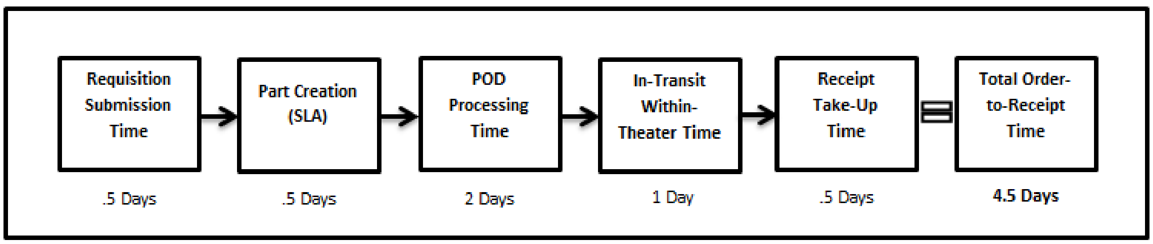

Figure 12. Resupply Process Flowchart for Category 1, Area D Utilizing SLA

As a result of incorporating SLA to produce a Category 1 part, the total order-to-receipt time was 4.5 days. The order-to-receipt time was reduced by 9.5 days, or approximately 68 percent.

3. Incorporating FDM

Next, we incorporated FDM into our process flowchart and eliminated the steps associated with processing and delivering parts in the CONUS. The times associated with all other steps in the process were unchanged. Figure 13 represents our flowchart illustrating the incorporation of FDM into the aerial resupply operation.

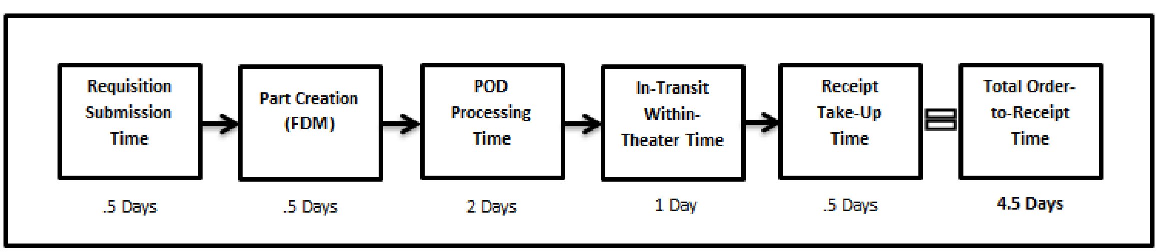

Figure 13. Resupply Process Flowchart for Category 1, Area D Utilizing FDM

As a result of incorporating FDM to produce a Category 1 part, the total order-to-receipt time was 4.5 days. The order-to-receipt time was reduced by 9.5 days, or approximately 68 percent.

4. Incorporating SLS/DMLS

Next, we incorporated SLS and DMLS into our flowchart and eliminated the steps associated with processing and delivering parts in the CONUS. The times associated with all other steps in the process were unchanged. Figure 14 represents our flowchart illustrating the incorporation of SLS into the aerial resupply operation, and Figure 15 illustrates the incorporation of DMLS for producing metal parts.

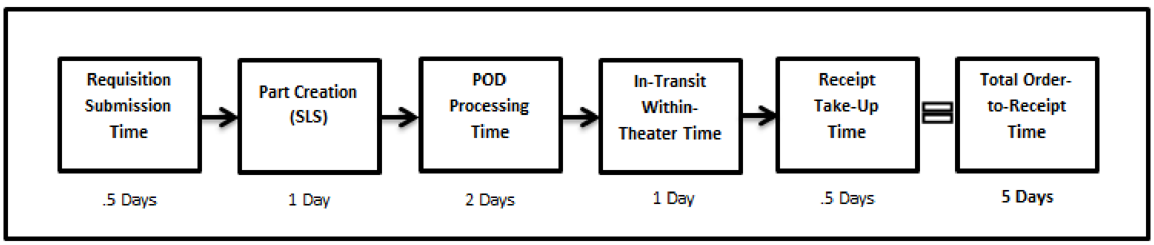

Figure 14. Resupply Process Flowchart for Category 1, Area D Utilizing SLS

As a result of incorporating SLS to produce a Category 1 part, the total order-to-receipt time was five days. The order-to-receipt time was reduced by nine days or approximately 64 percent.

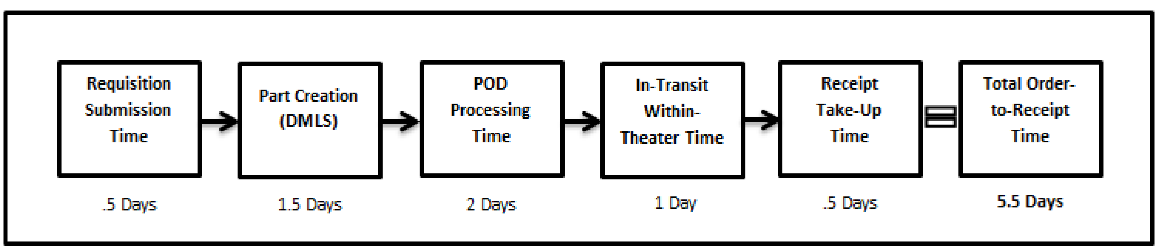

Figure 15. Resupply Process Flowchart for Category 1, Area D Utilizing DMLS

As a result of incorporating DMLS to produce a Category 1 part, the total order-to-receipt time was 5.5 days. The order-to-receipt time was reduced by 8.5 days or approximately 61 percent.

5. OIF Analysis

In Chapter III, we created a table (Table 2) based on the processes and times graphically illustrated in Figure 9. In order to evaluate the impact AM can have on Army logistics; we incorporated our estimates into our process flowchart. The purpose of this flowchart is to illustrate the impact AM could have made if the technology had been mature enough and available during the early phases of OIF. Figures 16 and 17 illustrate the steps and times presented in Table 2.

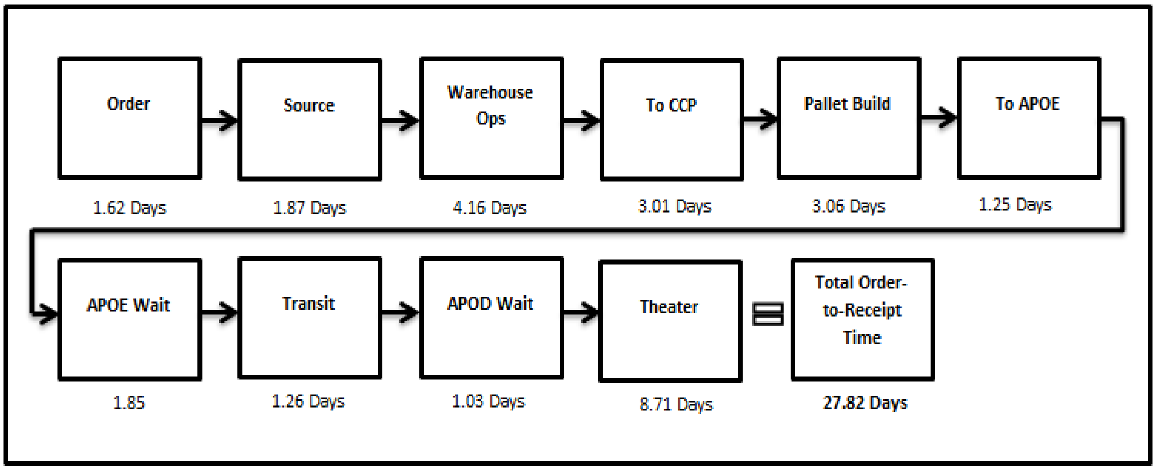

Figure 16. Aerial Resupply Process Flowchart (Estimated) During OIF—2003

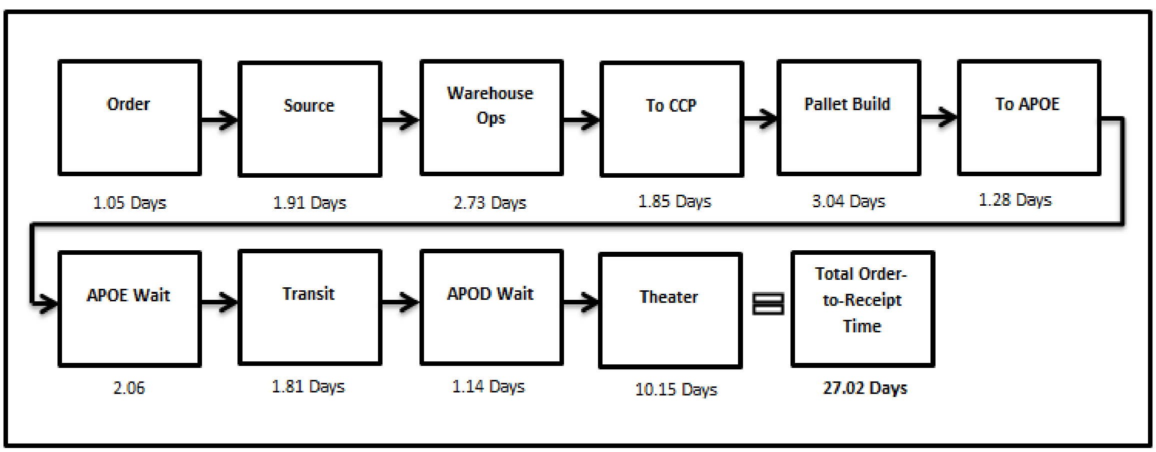

Figure 17. Aerial Resupply Process Flowchart (Estimated) During OIF—2004

In order to illustrate the theoretical changes in part resupply times using AM, we created tables instead of individual flowcharts. We removed steps involving CONUS operations and left the times associated with all other processes unchanged. We then inserted the times for each AM process and calculated the reduction in days and the percentage of change. Table 3 illustrates the theoretical benefits AM could have provided in 2003.

Table 3. Aerial Resupply Times (Estimated) Utilizing AM During OIF—2003

	Aerial Resupply Process/Times (in days)					
	Order	**Part Creation**	**Theater**	**Total**	**Days Reduced**	**%**
SLA	0.5	0.5	8.71	9.71	18.11	65.10%
FDM	0.5	0.5	8.71	9.71	18.11	65.10%
SLS	0.5	1	8.71	10.21	17.61	63.30%
DMLS	0.5	1.5	8.71	10.71	17.11	61.50%

As Table 3 demonstrates, the number of order-to-receipt time days could have been reduced anywhere from 17.11 to 18.11 days, and the percent reduction ranged from 61.5 percent to 65.1 percent.

Table 4 illustrates the theoretical benefits AM could have provided in 2004. If the technology had been mature and available in 2004, the number of order-to-receipt time days could have been reduced anywhere from 15.67 to 16.67 days, and the percent reduction could have ranged from 56.33 percent to 59.92 percent.

Table 4. Aerial Resupply Times (Estimated) Utilizing AM During OIF—2004

	Aerial Resupply Process/Times (in days)					
	Order	**Part Creation**	**Theater**	**Total**	**Days Reduced**	**%**
SLA	0.5	0.5	10.15	11.15	16.67	59.92%
FDM	0.5	0.5	10.15	11.15	16.67	59.92%
SLS	0.5	1	10.15	11.65	16.17	58.12%
DMLS	0.5	1.5	10.15	12.15	15.67	56.33%

C. RESULTS

Based on our analysis, AM can potentially reduce order-to-receipt by 8.5 to 9.5 days (60.71 percent to 67.85 percent) compared to the TDD standards. Additionally, had the technology been mature enough for use during the early stages of OIF, order-to-receipt time could have been reduced by 15.67 to 18.11 days (56.33 percent to 65.10 percent). These results are based on conservative assumptions. Reducing the distance between customer and AM capability could potentially reduce order-to-receipt time even further.

D. SUMMARY

In this chapter, we applied our findings from Chapters II, III, and IV to analyze how AM can impact aerial resupply operation in theater. First, we applied the primary AM processes to the TDD standards for Category 1 requisitions. Next, we applied the AM processes to the early stages of OIF. Finally, we concluded that AM could significantly reduce order-to-receipt time in combat operations.

VI. SUMMARY, CONCLUSION, AND AREAS FOR FURTHER RESEARCH

A. SUMMARY

The purpose of this research project was to increase our understanding of AM technology and how it can improve Army logistics in the future. By narrowing our focus to the three research questions posed, we set goals to determine what the Army could learn from industry, understand the current state of the AM technology, and realize the potential benefits of AM technology. We hope our research will increase interest in AM and lead to further research on the topic.

In the first chapter, we laid the foundation for our research. In the second chapter, or literature review, we introduced the primary methods of AM. By researching these methods, we were able to determine how the parts were made, the types of materials that could be used, and the size and speed in which parts can be produced. We then provided industry and military examples of AM technology in use. By researching industry and military examples, we were able to identify the benefits and limitations of the technology. Finally, we provided a glimpse into the future of AM.

Next, we examined a study on logistics operations during OIF and the TDD standards for aerial resupply of parts. The recent reports of AM being utilized in Afghanistan spurred our interest in how this technology could impact maintenance downtime that results from waiting for parts. The RAND study and DoD 4140-R provided our basis for analysis of how AM could eliminate the CONUS-to-theater segment of the supply chain.

In Chapter IV, we explained the methodology of our research, presented our model, and identified the assumptions used in our analysis. In Chapter V, we applied the results of our research to our model in order to analyze how AM could impact order-to-wait time. We utilized the model to measure the difference in order-to-wait time when applied to the TDD standards and to statistics from OIF.

B. CONCLUSION

1. Research Findings

Our three initial research questions were as follows:

- What benefits have been realized as a result of incorporating AM in industry?
- What are the limitations of AM?
- How can incorporating AM into Army operations in a deployed environment impact resupply operations?

Regarding our first research question, many benefits have been realized as a result of incorporating AM into industry. These benefits include, but are not limited to:

- cost reduction,
- low volume production,
- the ability to create complex objects,
- weight reduction through elimination of unnecessary material,
- waste reduction,
- production time reduction,
- tooling requirement reduction,
- the ability to rapidly create prototypes,
- and inventory reduction.

Regarding our second research question, there are some limitations to AM, including the following:

- AM is currently not suitable for high volume production,
- AM is limited to one material at a time,
- AM has a limited capacity,
- some methods of AM require lengthy post-processing, and
- AM is not fully mature for theater part reproduction.

Regarding our final research question, we concluded that incorporating AM into resupply operations can greatly reduce order-to-wait time. While the technology is not currently mature enough for full-rate part production in theater, our research suggests that in the future, AM could transform the way we deploy and sustain forces. Our findings indicate AM's ability to reduce order-to-receipt time by more than 50 percent and upwards of 65 percent for parts requiring shipment from the CONUS.

These results were based off placing AM technology at the POD and producing one part at a time. The ability to produce multiple parts and the ability to place the technology at the brigade level could further reduce order-to-receipt time. While there are currently limitations regarding the parts that can be produced utilizing AM, as the technology evolves, the number of reproducible parts should increase.

2. Recommendations

Although the Army has already incorporated AM into some operations, we recommend that research continues in order to capitalize on the benefits that this technology can provide now and in the future. The ability to create parts at the push of a button has the potential to greatly extend the life cycle of programs. Computer numerical control (CNC) manufacturing is commonly used to produce parts for systems where parts are no longer manufactured. AM has the ability to provide this same capability, while producing less waste in the process.

C. AREAS FOR FURTHER RESEARCH

Our research only scratches the surface of capabilities AM can provide to the Army. While our analysis was based off assumptions, a researcher with access to all three primary methods of AM could create parts in order to obtain more accurate time samples. Research on the amount of commonly ordered parts made out of single materials could be done to determine how much the logistics footprint could potentially be reduced. In addition to reducing the logistics footprint, research regarding shipment reduction and cost savings could be beneficial as well. Finally, this research could be applied to other branches of service, particularly the Navy, where AM at sea could impact operations.

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